

## Understanding Machinery Management – Using Machine Condition and Process Information for Maximum Benefit



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Industry has found that implementation of advanced, computerized process control instrumentation and automation systems, such as Distributed Control Systems (DCS), have resulted in significant improvements by controlling and managing their processes much better than older technologies. A strong focus on getting the most out of the process – proactive process management – remains.

There is increased awareness, however, that the push towards lowest possible cost of production and excellent manufacturing flexibility requires that the equipment assets used to run the process be extremely reliable. There are “windows of opportunity” during which plants can sell all their product output, usually at a premium price, and the ability to run at capacity during these times, or even slightly above capacity, can make a huge difference in terms of profitability.

Proper management of equipment assets affects production costs. When maintenance can be performed knowledgeably and only when needed, costs can be reduced. As efforts to maximize and optimize the process have occurred, additional stress on the mechanical assets may have been introduced, resulting in higher support costs. In some cases, the increased asset support costs may exceed the additional process benefits. Clearly, the impacts need to be known and understood.

Very simply, asset management is the practice of using and maintaining assets knowledgeably, to strike a business balance between optimal process output and optimal asset support costs. The process and the assets are highly inter-related, each affecting the other, and they cannot effectively be managed in isolation. Historically, Operations departments have been focused almost exclusively on the process aspects

of the business, with minimal involvement in understanding the effects of the process on the life of, or maintenance implications to, the actual machinery assets themselves. This is changing. Asset management measures the effect of the process on the physical assets with online measurements. Increased production through greater asset availability is the goal. It attempts to optimize the productivity of the assets while minimizing their cost of ownership.

Machinery management is a subset of asset management. It focuses on a specific class of mechanical assets highly important to the process industries, rotating and reciprocating machinery, and it represents tremendous opportunity.

### Machinery Protection

A more detailed discussion of machinery management needs to be prefaced by a description of machinery protection, which is the use of systems that shut a machine down or return it to a safe or nondestructive mode of operation without human intervention. Machinery protection systems have been in widespread use since the late 1960s. They consist of appropriate transducers (vibration, position, temperature, flow,

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pressure, speed, etc.) coupled with continuous, permanent monitoring instruments capable of sending alarm and shut-down commands to the machinery control system. In essence, machinery *protection* is an extreme form of machinery *management* that uses available measurements and data to automatically shut the machine down when conditions degrade beyond pre-established alarm limits. By design, the levels used to shut a machine down or remove it from service are generally quite high. Shutdown only occurs when conditions degrade such that safety is jeopardized or total asset failure is imminent.

Machinery protection systems continue to be an important part of an overall asset management program because asset failure can occur without warning. Machinery protection systems may prevent such catastrophes, but they do not permit the user to be proactive. In fact, their very design keeps the instrument from taking action until conditions have significantly degraded. In other words, they don't "protect" the machine's ability to keep running, they merely minimize collateral damage once failure has progressed to severe levels.

*"Machine service is just as important as machine size in assessing its criticality."*

### Classes of Machinery

Machinery assets are generally categorized according to their impact on the business. Machinery may be considered *critical*, for example, if it represents such large business risks including economic, safety, government compliance, or production/process interruption that mechanical failures cannot be tolerated. *Essential* machinery can cause partial production interruption or some other form of business loss if it fails, does not run, or runs at reduced capacity. *Balance-of-plant* (also referred to as general purpose) machinery includes all plant machinery considered neither critical or essential. It is important to note that while machine size generally corresponds to its criticality, "small" machines may indeed be critical or essential. A "small" machine, for example, may handle toxic substances where a seal failure results in emissions. The same type of machine might be used elsewhere in the plant handling a non-toxic substance such as water and whose service does not directly impact production or safety. Machine service is just as important as machine size in assessing its criticality.

It is generally recognized as good engineering and business practice to protect all critical and essential machinery in a plant. Machinery protection systems are frequently used to ensure personnel safety, prevent or minimize machine damage, and limit environmental impact.

Balance-of-plant machinery may not justify machinery protection. The primary focus on these machines is to collect data periodically such that machine condition can be ascertained, maintenance can be performed only when needed and only on those machine components that require repair or replacement, and costs can be optimized. The sheer volume of balance-of-plant machines in many plants means that maintenance costs can be substantial and offer numerous

opportunities for reduction. Indeed, balance-of-plant equipment may make up the majority of the maintenance budget.

Critical and essential machinery, on the other hand, often have a slightly different focus for justification of machinery management. While maintenance costs are a concern, it is typically the undesirability of failures and the resulting partial or total loss of production that drives the user toward machinery management. These often eclipse maintenance-related costs and can run as high as hundreds of thousands of U.S. dollars per hour of lost production.

Good engineering and business practice dictates that all machinery classes be managed. Regardless of the category of plant machinery, availability and reliability need to be optimized. Today's objective should be to provide plant experts with the means to be able to focus 100% of their time and expertise only on those machines that require corrective action. (This is called exception management.) This can only be accomplished with modern machinery management, and only when the output of the machinery management system targets Operations *and* Management personnel, not just Maintenance personnel and machinery specialists. New and advanced technologies mean that *all* plant machinery, not just the large critical ones, need to be proactively managed.

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### Machinery Management

Machinery management starts with making the right measurements and reducing the data into meaningful formats. The data collection and reduction process can be manual or automatic. The data reduction process is almost always automatic and done in a computerized system. However, the data collection process is often manual, particularly for balance-of-plant and essential machinery, using portable, hand-held data collection instruments that take snapshot data samples at all relevant monitoring points on a periodic basis. Critical machinery, in contrast, is often fitted with permanent online data acquisition equipment such that data can be collected at high speed, from all channels simultaneously, and at frequent intervals (seconds) during steady-state, upset, transient, or alarm conditions.

One other automated data acquisition strategy is beginning to emerge that bridges the gap between portable and continuous, high-speed data collection. It is a scanning strategy that gathers data at longer intervals (typically every few minutes) using permanently installed instruments. It is not appropriate for critical machinery, but can be extremely effective for essential and balance-of-plant machines. Because the system acquires data less frequently, it can generally be applied to a broader range of machinery at relatively low costs. Both wired systems using a “bus” style architecture where many measurement points can be accommodated on a single cable, and newer, wireless systems are available.

*“Users that routinely derive the most value from a system and experience the fastest payback are those that learn to use it as an operations tool, not just a maintenance planning and machinery diagnosis tool.”*

### Portable (Offline) Systems

Proponents of portable data collection approaches cite their relatively low equipment cost (typically, 20,000 USD to 30,000 USD for data collector and software) and their flexibility (measurements can be made when and where needed using portable transducers). Portable programs, however, suffer from high recurring costs because manual labor is required to periodically collect data. “Periodic data collection” can mean anything from once every few weeks to once per quarter or longer. The data collection intervals generally depend on the available manpower, the time required to physically collect and process the data, and the relative machine importance. Regardless of the collection period, this approach results in moving people (rather than data), sometimes at considerable cost. Though this may be the optimum balance-of-plant data collection program in some cases, in others it will fall far short of what can be achieved. A refinery, for example, internally assessed its portable data collection program and found that of the ~2000 general purpose machinery data points sampled in a month, 80% of machines were within acceptable limits, having no significant change; the remaining 20% required further investigation or a corrective action plan. In other words, 80% of the available time was being spent physically collecting and reducing data from perfectly good machines.

Portable data collection suffers from another fundamental shortcoming: it cannot be used to correlate the machine’s mechanical stress with process changes. Thus, the actual process conditions that may stress the machine and lead to failure are not known. Failures can be detected and maintenance can be scheduled, but the root cause conditions which “kill” the asset are never properly understood or addressed.

### Online Systems

Online machinery management systems are of two types: continuous and scanning. Continuous systems are typically appropriate for the most critical machines in the plant because they acquire data continually from many channels simultaneously. The costs for such systems are comparatively high, but the ability to manage the machine via collection of data at frequent intervals and from numerous transducers is justified because it permits management decisions to be made with a high level of certainty. Scanning systems eliminate the need for manual data collection. Although they have higher initial costs than offline systems, they may represent the lowest life-cycle costs and provide adequate data acquisition for essential and balance-of-plant machinery. Both types of online systems facilitate the critically important ability to collect both process and machinery data simultaneously.

Process data is the measurement of parameters associated with the process stream flowing through the machine and the machine’s surrounding environment (Table 1). Machine condition data correlated with process data allows the root causes of failure to be better understood because the interaction between machine and process can be observed and trended.

When automated knowledge-based systems are employed to reduce machinery and process data into actionable recommendations, personnel utilization is significantly improved. People can focus on machines that the system identifies as needing attention. This is the process of exception management. The system can provide recommended actions to the appropriate individuals. Importantly, these systems, like process control systems, have evolved to provide data to the people often in the best position to take immediate action when machinery assets undergo stress – operators. Thus, the machinery management system becomes part of a “feedback loop” to operators regarding the condition of the machines and their interaction with process conditions. Users that routinely derive the most value from a system and experience the fastest payback are those that learn to use it as an *operations* tool, not just a maintenance planning and machinery

### Gas Turbines

- Ambient temperature and pressure
- Inlet pressure and temperature
- Discharge pressure and temperature
- Inlet guide vane (IGV) position
- NO<sub>x</sub> water injection rates (if applicable)
- Total power generated (kW) or shaft speed and torque
- Kvars (generator drive applications)
- Fuel heating value
- Relative or absolute humidity
- Exhaust gas temperature
- Fuel flow
- Bearing metal and oil drain temperatures

### Steam Turbines

- Steam supply and exhaust conditions – temperature, pressure, flow, quality
- Extraction conditions (if applicable)
- Condenser vacuum
- Gross generation (kW) or shaft speed and torque
- Reheat steam conditions (if applicable)
- Kvars (generator drive applications)
- Bearing metal and oil drain temperatures

### Centrifugal Compressors

- Suction pressure and temperature
- Discharge pressure and temperature
- Product (gas) flow rate
- Gas analysis (mole weight)
- Compressor speed
- Driver power
- Bearing metal and oil drain temperatures

### Centrifugal Pumps

- Speed
- Suction pressure and temperature
- Discharge pressure and temperature
- Flow
- Driver power
- Bearing metal and oil drain temperatures

### Generators

- Output (kW or MW)
- Reactive loading (vars)
- Power factor
- Coolant gas temperature and pressure
- Winding temperatures
- Field current
- Bearing metal and oil drain temperatures

diagnosis tool. They alter their business and operational procedures to use and act on machinery information in real time, and as a result benefits are quickly realized.

### Best Practice

Machinery management represents a new paradigm. Consider Figure 1. In level 1, sensors on the machine input to the control system, and separate sensors are input to the machinery protection system. As machinery stress level rises (Figure 2), a first level alarm (“Alert”) in the protection system is activated at time  $T_1$ . The result is typically a flashing light on the system’s front panel. A responsible individual really has no additional data at that point. A person with portable instrumentation may be called to help troubleshoot the machinery and provide some understanding of its condition, but the process is reactive; it provides no historical data on how or why machine condition has degraded, and it can take considerable time (i.e., from hours to days) to arrive at a conclusion. In some cases, the necessary data will simply not exist because the conditions triggering the degradation occurred long before and were not being measured. As illustrated, machine stress will often simply continue to increase to the “Danger” level ( $T_2$ ), at which point the machinery protection system shuts the machine down. In this scenario, the plant may or may not be able to discover what is wrong. It is highly unlikely, however, that they will discover why or be able to proactively do anything about it before machine conditions degrade further. If the machinery protection system shuts down the machine, the tendency may be to consider it a “machinery save,” but as previously mentioned, the process stream must be interrupted. This represents **lost opportunity** and is one of the most significant costs associated with **not** managing machinery.

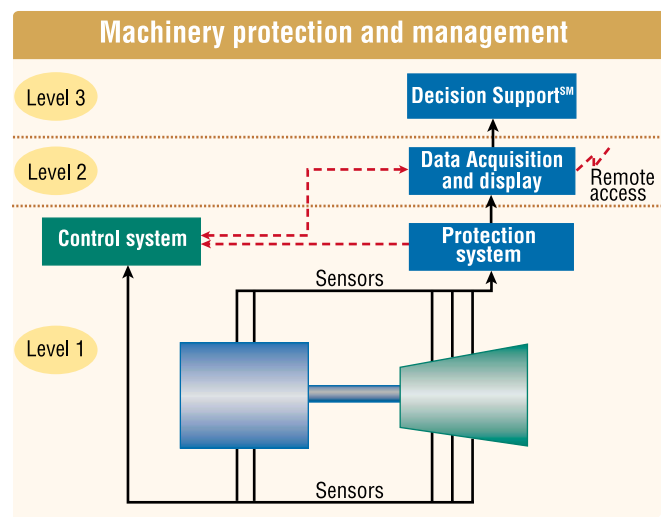
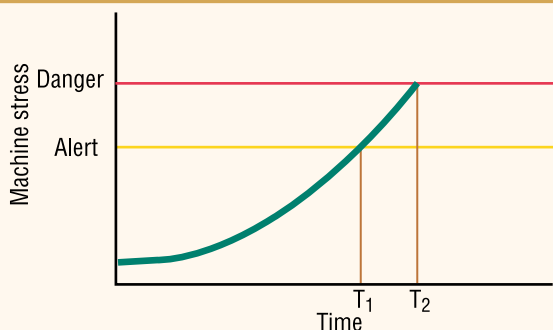


Figure 1.

Table 1.

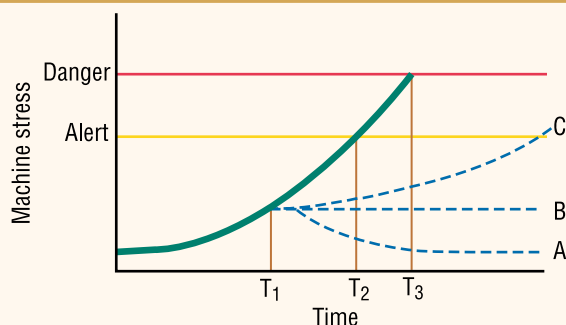
### Alarms occur on a machinery protection system as a result of increasing stress



**Figure 2.**

Better is level 2 in Figure 1, that uses data acquisition equipment typically consisting of high-speed sampling hardware and computer(s). It allows the capture of machinery data for additional processing and archival. This data may be shared with the control system and is available remotely. Informative plots can be generated and reviewed to aid in troubleshooting, but the activity remains labor intensive. There may or may not be process data. Machinery condition is still required to trigger an “Alert” level in the protection system before awareness of a problem occurs. This approach provides more, and better, data, but it is also reactive. The time for someone to take corrective action may be shorter than in the first scenario, but may not be short enough, as plots and data need to be reviewed and correlated with process conditions before knowledgeable decisions can be made. Because this approach is so labor intensive and requires manual review of so much data and plots, it frequently becomes a reactive task. While someone could theoretically use such a system proactively, this almost never occurs in practice because the time and personnel resources required to continually review data is not practical. Unless a machinery management system can be employed proactively, it can never address the “lost opportunity” costs mentioned above.

### Machinery management is managing below the alarm light



**Figure 3.**

Preferable is level 3 in Figure 1. With the necessary knowledge base and decision support capability, there is now ability to proactively “manage the machine below the alarm light level.” As illustrated in Figure 3, when stress increases ( $T_1$ ), but well below an alarm condition, information from the machinery management system enables the responsible individual to take action. Based on the action taken, machinery stress may: A) return to a lower level; B) maintain its current level; or C) continue to increase, but at a reduced rate that allows additional time to effectively plan maintenance activities.

Best practice today means using machinery management systems that ...

- are online, allowing continuous data collection as well as remote access for timely collaboration from anywhere as needed
- incorporate the right measurements of the equipment under observation to give sufficient data
- reduce the data to appropriate presentation formats (plots)
- are knowledge-based, converting the data to information by applying engineering principles as to how the machinery responds to the process, behaves mechanically, wears, and fails
- output information that is actionable – that is, targeted and usable by the appropriate responsible individual for decision support – allowing adjustments to the equipment, to the process, or both.
- addresses all classes of machinery assets, whether critical, essential, or balance-of-plant.

### Benefits

Common benefits can be categorized as follows:

*Increased safety* – Machinery management enables companies to conduct responsible care. Safety is improved for plant Maintenance and Operations personnel when the health of the machine is known. Safe operation of machinery results in no lost time accidents due to machinery failures. Similarly, environmental events (releases) that might result from machinery failure are eliminated.

*Enhanced availability and operations flexibility* – Proper machinery management means that, when the condition of a machine changes, enough data is available to detect the change early and to provide an accurate evaluation of the machine stress level. Based on the evaluation, action plans and business plans can be implemented to limit the process impact caused by the change in the machine’s condition. When



machinery is down, it cannot contribute to the production of product. That may mean significant unrealized revenue. Avoiding such situations requires knowledge not only of the real-time condition of the equipment, but also of what its normal condition and behavior are, and it requires answers to key questions like: How efficiently is it performing the desired work? How long will it be able to do this reliably? Can the process be adjusted to extend the run and avoid a shutdown? With answers to such questions, operators can play a direct role in machinery stress management. Stress can be monitored and managed in an optimal way, within acceptable long-term limits. Product can be supplied more reliably, and production opportunities can be maximized.

*Improved utilization of personnel* – The number of personnel at many plants is decreasing, and there is a basic desire to do more with fewer people. Dedicated machinery personnel are generally in shorter supply. They simply do not have time to focus on regular review of all collected data. They must manage their machinery assets by exception, spending time only on those machines where something has changed from “acceptable” conditions. A machinery management system can automate the process of reviewing data and can play a significant role in improving human resource utilization.

*Time between planned maintenance outages may be safely and economically extended in some situations* – Maintenance can be performed as conditions require rather than simply based on the passage of time. Knowing in advance if and when a machine is going to fail is a tremendous advantage. Necessary downtime can be scheduled and planned ahead of time. Maintenance requirements (e.g., labor, parts) can be anticipated and more effectively used, leading to substantial maintenance cost savings.

*Substantial economic returns* – Companies simply cannot undertake all projects that might be considered. Projects must be prioritized, and this is often accomplished by evaluating their anticipated return on investment (ROI). Those that represent the highest ROI (and consequently the quickest payback) are more likely to be done. Many companies have found there are substantial returns to investments in machinery

management systems. Returns vary, as location-specific conditions and events, and company-specific practices for determining associated economic benefits differ. Nevertheless, paybacks within a matter of months are typical, and they almost always occur within the first year. When faced with a crisis or troubled operating mode, the availability of immediate expert advice can be so valuable that a system can pay for itself several times over during a single event. A process capable of generating substantial revenues can be kept in operation or an expensive critical machine can be saved from damaging itself and surrounding plant. Significant returns not only result from managing large, critical machinery but also result from managing balance-of-plant machinery whose aggregate plant numbers may be in the hundreds or even thousands.

### Case History #1

An offshore platform located in the North Sea is a fully staffed gas production facility. The gas is exported through pipelines to a terminal on shore.

Two new gas compressor units were installed on the platform in order to continue gas production as the field pressure decreased. Each unit consists of a 14 MW aeroderivative gas turbine, a power turbine, a speed increasing gearbox, and a back-to-back type barrel compressor (Figure 4). The units are designed to run separately or in parallel with each other.

Since safety is a primary issue on offshore platforms, and because the two compressors are essential for gas production, the machinery was equipped with vibration and thrust position transducers. The transducers were connected to online monitors and a machinery management system that continuously collects and stores data from all machinery protection system inputs

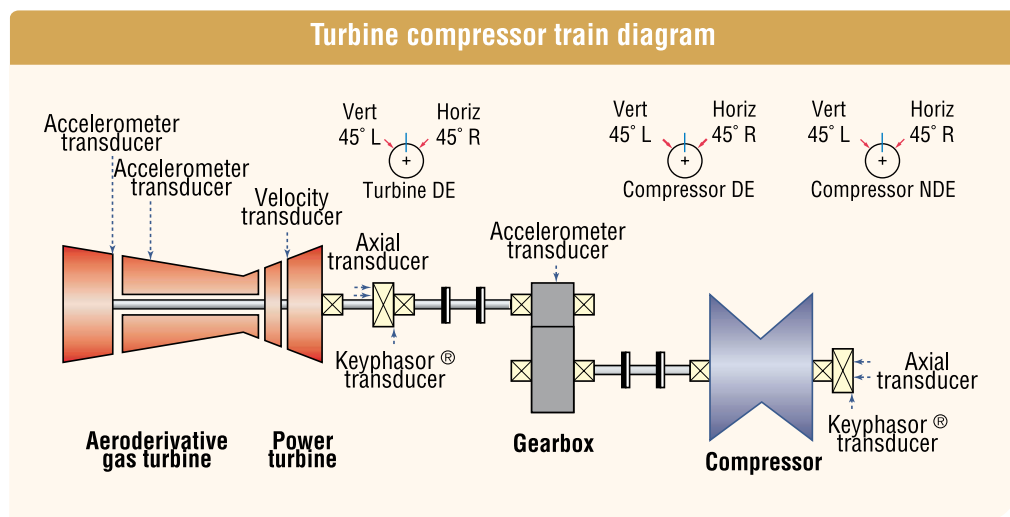


Figure 4.

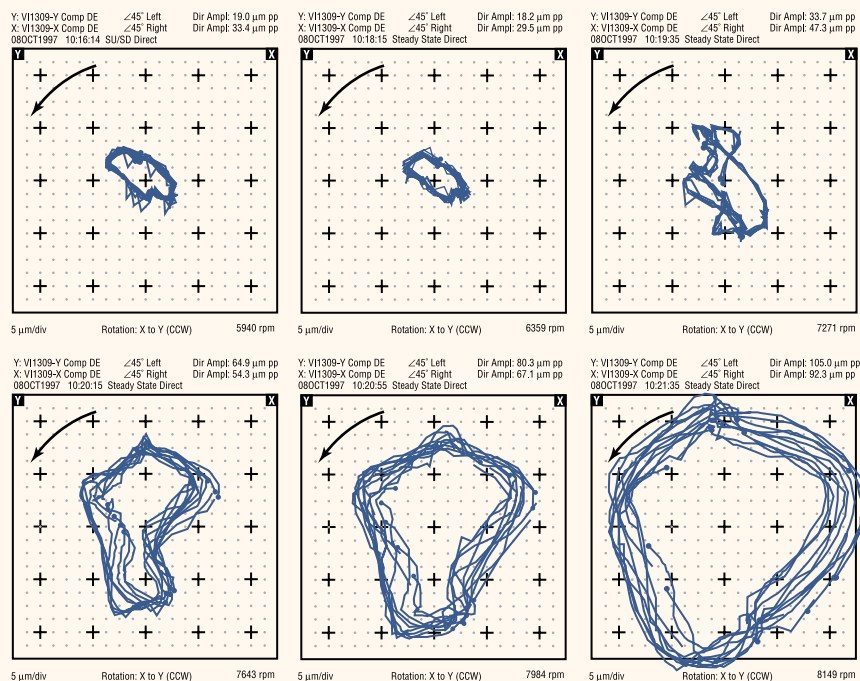
during steady state operation and also during important operating conditions, such as transient operation (startup and shutdown) and protection system alarms. This data is used to evaluate the machine's condition and to optimize the operation of the compressors.

The machinery management system offers access to both real-time and archived data files via a modem connection. Remote diagnostics is possible from any land-based location, enhancing the ability to rapidly resolve machinery problems.

A request was made to monitor the startup of the compressors via a modem connection. The unit ran up to nearly 7000 rpm without any problems. At 7200 rpm the compressor suddenly experienced high vibration amplitude. Within 2½ minutes, as the speed continued to increase, the vibration amplitude increased from 10 to 110 µm (0.4 to 4.3 mils) peak-to-peak (pp), and the unit tripped. A diagnosis of all the vibration data was performed online, and a root cause conclusion was reached. The analysis was completed in approximately 2 hours.

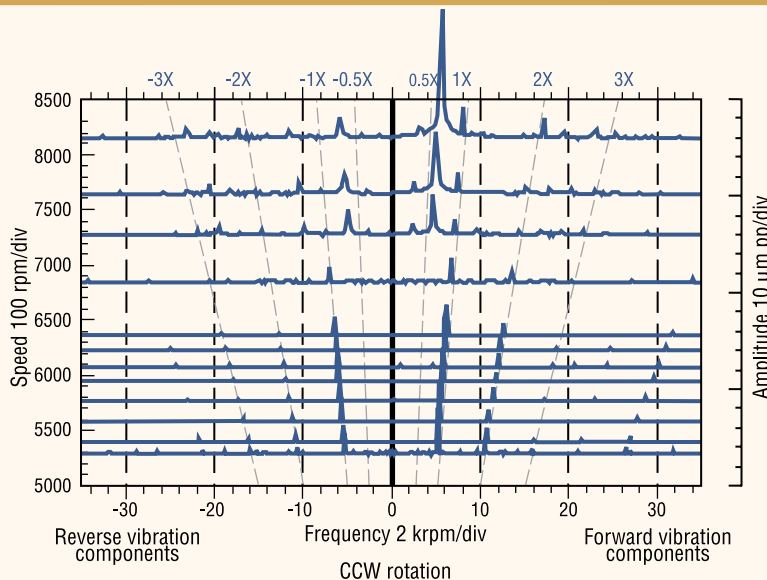
The vibration data up to 7000 rpm showed that 1X (at running speed) vibration was the predominant vibration frequency. At 7200 rpm the machine's vibration response became unstable, and a subsynchronous vibration was the major vibration component (Figure 5). The vibration full spectrum cascade plot shows that this subsynchronous component is forward and at approximately 0.65X running speed (Figure 6). Rotating stall can be recognized by subsynchronous vibrations, typically at 0.10X to 0.20X rotative speed, when the action occurs in the diffuser, and at 0.60X to 0.80X rotative speed, when the action occurs in the impeller. Rotating stall is an instability of the coupled aerodynamic/mechanical system resulting in whirling of a rotor at a subsynchronous frequency, which tracks the rotative speed. It is caused by boundary layer separation in the compressor which results in partial flow reversal in the impellers and circumferentially propagating pressure waves.

**The orbit patterns during the startup of the compressor. At 7271 rpm the orbit shape is dominated by a subsynchronous vibration component caused by circumferentially propagating pressure waves in the impeller.**



**Figure 5.**

**The full spectrum cascade plot indicates the subsynchronous vibration is tracking running speed at 0.65X and is forward in precession.**



**Figure 6.**

The suction pipe to the compressor was removed. The suction pipe was supposed to contain a metal cone-shaped filter. This filter was missing. It was concluded that these parts had been sucked into the compressor, so a borescope

investigation was performed. As soon as the camera entered the compressor inlet, a large piece of the filter was visible, folded around the inlet splitter. This piece of filter, which clearly blocked a large part of the compressor inlet, was the reason for the rotating stall at the impeller.

The damaged inlet filter was removed and the compressor was back online in less than one day. Remote access of the machinery management system was critically important to this timely diagnosis. Catastrophic machine failure and significant loss of production was averted. Prior to completion of the diagnosis and inspection of the piping and compressor suction, platform personnel were making preparations to remove the compressor and send it to an onshore repair facility. Estimated turnaround time at the repair facility was seven days. At a gas production value of 300,000 USD per day, this would have represented 2,100,000 USD of lost production.

## Case History #2

An ethylene plant in the U.S. has five major compressor trains:

- **Train 1:** 35,000 hp charge gas compressor train. It provides the low pressure necessary at the cracking furnaces for high ethylene selectivity and the discharge pressure necessary to process the cracked gas through its cryogenic distillation system.
- **Train 2:** 35,000 hp propylene refrigeration compressor train. It provides the primary refrigeration for cryogenic distillation.
- **Train 3:** 6,000 hp ethylene refrigeration compressor train. This train provides a lower level of refrigeration for cryogenic distillation.
- **Train 4:** 3,500 hp purge propylene refrigeration compressor train. It supplies additional primary level refrigeration and refrigeration for the purge recovery facilities.
- **Train 5:** 2,500 hp methane compressor train. This train provides refrigeration for the hydrogen purification facility.

All of the compressor trains are single-line equipment; there are no installed spares. A shutdown of trains 1, 2, or 3 causes the entire ethylene plant to shut down. A shutdown of trains 4 or 5 will not necessarily cause an entire unit shutdown, but will significantly lower plant production. An ethylene plant shutdown, depending on the length of shutdown and the price of ethylene, can cost millions of U.S. dollars in lost revenue.

In the past, each machine was opened up every two years. Today, machinery is managed, often running three years without maintenance. Machinery may run as long as nine years before a major overhaul, at which time, nondestructive fatigue testing is done.

The plant's machinery management system helped identify a fluid-induced instability on the 4-stage charge gas compressor, and helped maintain production levels until a scheduled shutdown, saving approximately US \$2,500,000 in production.

Subsynchronous vibration levels increased on Stages 3 and 4 of the charge gas compressor; however, vibration levels were more predominant on Stage 4. Subsynchronous vibration levels reached 76  $\mu\text{m}$  (3 mils) pp, and would then disappear. The frequency of the subsynchronous vibration on Stage 4 also varied, from 0.38 to 0.50 times running speed. Subsynchronous vibration also became evident on the compressor's second and third stages, which share a common case and rotor. By the end of the month, the subsynchronous vibration was continuous at levels of 76  $\mu\text{m}$  to 127  $\mu\text{m}$  (3 to 5 mils) pp, causing serious concern.

The machinery management system indicated that the machine had fluid-induced instabilities. However, the plant could not be shut down because ethylene was selling at record high prices and was not available on the spot market.

The compressor's alignment was adjusted online, to change the load on the bearings, and stabilize the machine. Steam and water were used to heat and cool the compressor's support structure, which then changed the alignment and the load on the bearing. Water was sprayed on the outside of the volute, in an attempt to change the balance seal clearance. Using these techniques, subsynchronous vibration was controlled. The machinery management system was continually monitored.

The instability sometimes reappeared due to changes in load, and at times progressed to a light rub. To protect the machine from a hard rub and subsequent damage while production continued, an interlock driven by a machinery monitor was installed. At one times (1X) running speed, the compressor's overall vibration averaged 6  $\mu\text{m}$  (0.25 mil) pp. The interlock was set to shut down the system when vibration reached 25  $\mu\text{m}$  (1 mil) pp at 1X running speed.

The compressor was operated until its scheduled shutdown, which gave plant personnel time to analyze the problem and determine the correct modification necessary to eliminate the problem. It was determined that the compressor had an aerodynamic cross coupling problem. Several potential




fixes, such as a shunt in the balance seals, honeycombed seals, and TAM seals, were analyzed. After all factors were considered, such as stability improvement, fouling susceptibility, and clearance tolerances, balance seals modified with a radial shunt were selected as having the best potential for solving the problem. In addition, the analysis indicated that a change to a load-on-pad bearing arrangement would improve the stability characteristics of the rotor systems.

The Original Equipment Manufacturer (OEM) later built two new balance seals with radial shunts and modified the bearings to load-on-pad bearings. The compressor has not had any indication of an instability problem since.

## Conclusion

A significant part of most process plant assets is rotating and reciprocating machinery. Machinery management is a specific type of asset management. Its implementation enables better business decisions to be made about how machines and plants are operated and typically results in rapid, substantial financial returns. Machinery management represents a new approach, one that enhances the ability of machinery assets to contribute to plant production and revenue generation, as efficiency and reliability are increased, and downtime is minimized along with overall operation and maintenance costs. Good engineering and business practice dictates that *all* machinery should be managed.

To proactively manage machinery and optimize its performance along with the process, an effective machinery management system is required. Machinery management systems offer decision support by providing prioritized actionable information to operators, maintenance personnel, plant management, and others.

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